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**ADVANCED TURBOPROP AIRCRAFT FLYOVER
NOISE: ANNOYANCE TO COUNTER-ROTATING-
PROPELLER CONFIGURATIONS WITH AN
EQUAL NUMBER OF BLADES ON EACH ROTOR
-- PRELIMINARY RESULTS**

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(NASA-TM-100612) ADVANCED TURBOPROP
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ADVANCED TURBOPROP AIRCRAFT FLYOVER NOISE: ANNOYANCE TO COUNTER-ROTATING-PROPELLER CONFIGURATIONS WITH AN EQUAL NUMBER OF BLADES ON EACH ROTOR

Preliminary Results

David A. McCurdy

ABSTRACT

A laboratory experiment was conducted to quantify the annoyance of people to the flyover noise of advanced turboprop aircraft with counter-rotating propellers (CRP) having an equal number of blades on each rotor ($n \times n$, e.g. 8×8 , 10×10). The objectives were: (1) compare annoyance to $n \times n$ CRP advanced turboprop aircraft with annoyance to conventional turboprop and jet aircraft; (2) determine the effects of tonal content on annoyance; and (3) determine the ability of aircraft noise measurement procedures and corrections to predict annoyance for this new class of aircraft. A computer synthesis system was used to generate 27 realistic, time-varying simulations of advanced turboprop takeoff noise in which the tonal content was systematically varied to represent the factorial combinations of nine fundamental frequencies (blade passage frequencies), and three tone-to-broadband noise ratios. The fundamental frequencies, which represented blade numbers from 5 to 13, ranged from 112.5 to 292.5 Hz. The three tone-to-broadband noise ratios were 0, 15, and 30 dB. These advanced turboprop simulations along with recordings of five conventional turboprop takeoffs and five conventional jet takeoffs were presented at D-weighted sound pressure levels of 70, 80, and 90 dB to 64 subjects in an anechoic chamber. Analyses of the subjects' annoyance judgments compare the three categories of aircraft and examine the effects of the differences in tonal content among the advanced turboprop noises. The annoyance prediction ability of various noise measurement procedures and corrections is also examined.

SYMBOLS AND ABBREVIATIONS

ATP	advanced turboprop
CRP	counter-rotating-propeller
EPNL	effective perceived noise level, dB (ref. 1, 2)
F _o	fundamental frequency, Hz
FAR	Federal Aviation Regulation
L _A	A-weighted sound pressure level, dB (ref. 2)
L _D	D-weighted sound pressure level, dB (ref. 2)
L _E	E-weighted sound pressure level, dB (ref. 2)
L _S	subjective noise level, dB
L _L	loudness level (Stevens Mark VI procedure), dB (ref. 2)
L _{LZ}	Zwicker's loudness level, dB (ref. 2)
n	number of blades
P _L	perceived level (Stevens Mark VII procedure), dB (ref. 2)
P _{NL}	perceived noise level, dB (ref. 1, 2)
SRP	single-rotating-propeller
T ₁	EPNL tone correction method (ref. 1)
T ₂	tone correction method identical to T ₁ except that no corrections are applied for tones below the 500 Hz one-third-octave band
T/N	tone-to-broadband noise ratio

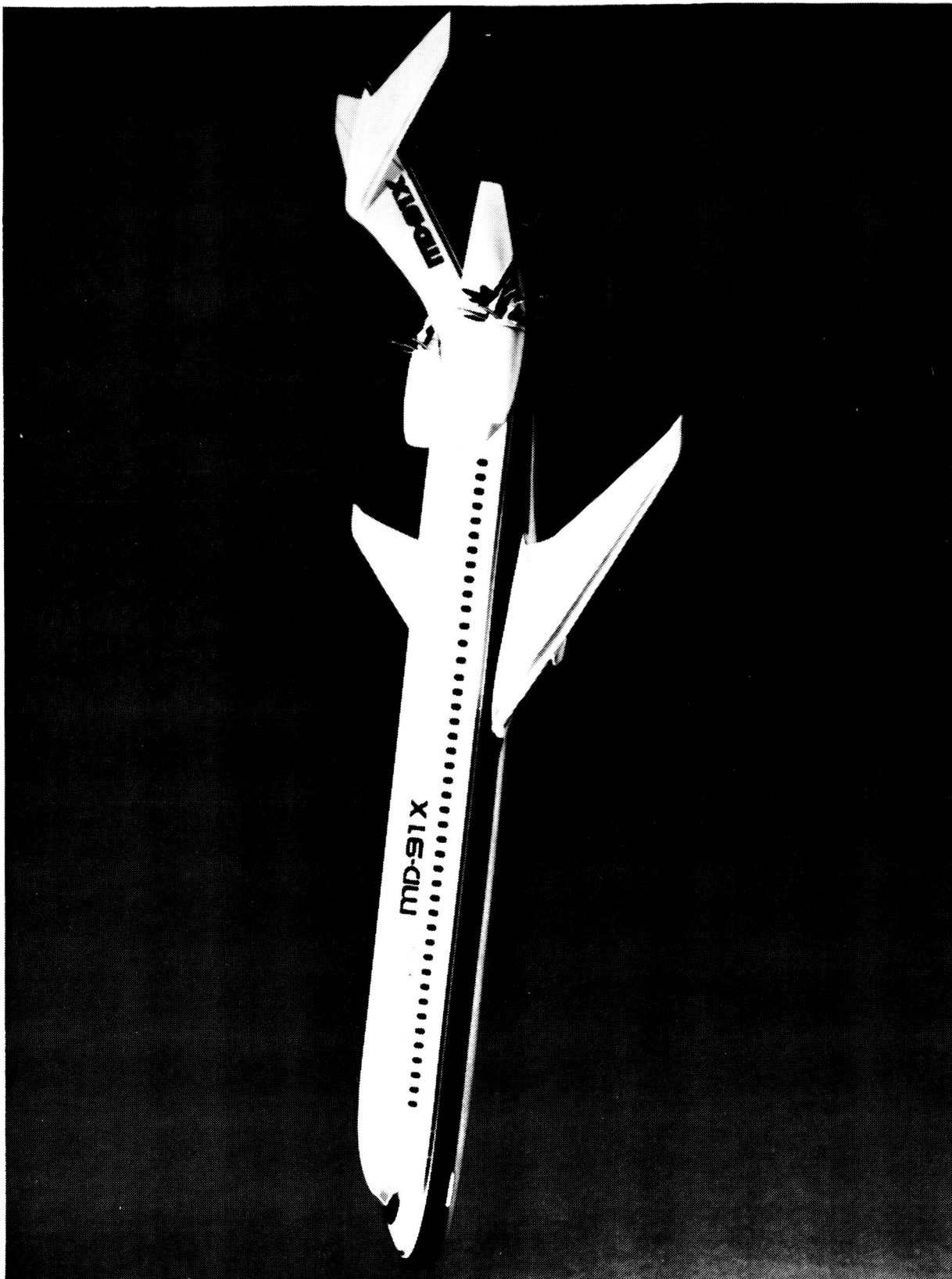


Figure 1. - An aft-mounted, pusher, counter-rotating-propeller configuration of an advanced turboprop aircraft.

INTRODUCTION

The return of the propeller to long haul commercial service may be rapidly approaching in the form of the advanced turboprop or "propfan" aircraft. The advanced turboprop propeller is vastly different from conventional propellers in shape and number of blades. Also, current design work indicates it will most likely be a counter-rotating propeller (CRP) instead of the conventional single-rotating propeller (SRP) configuration found on almost all of today's propeller-driven aircraft. The counter-rotating propeller consists of two rotors (or rows) of blades rotating in opposite directions around the same axis (fig. 1).

The advanced turboprop aircraft offers substantial savings in operating costs through improved energy efficiency. However, such an aircraft will come into general usage only if its noise, which has unique spectral characteristics, especially in the counter-rotating configuration, meets standards of community acceptability currently applied to existing aircraft. Much research has been directed towards understanding and quantifying the annoyance caused by jet aircraft flyover noise, but relatively little research has been conducted for conventional propeller noise and almost none has been done for advanced turboprop noise. To address this need, a laboratory experiment was conducted to quantify the annoyance of people to the flyover noise of advanced turboprop aircraft with counter-rotating propellers having an equal number of blades on each rotor and to compare that annoyance with the annoyance of people to conventional turboprop and jet aircraft flyover noise.

The laboratory experiment had three specific objectives. The first was to compare annoyance responses to the three categories of aircraft. The second objective was to determine the effects on annoyance of fundamental frequency and tone-to-broadband noise ratio. The last objective was to determine the ability of aircraft noise measurement procedures and corrections to predict annoyance for this new class of aircraft.

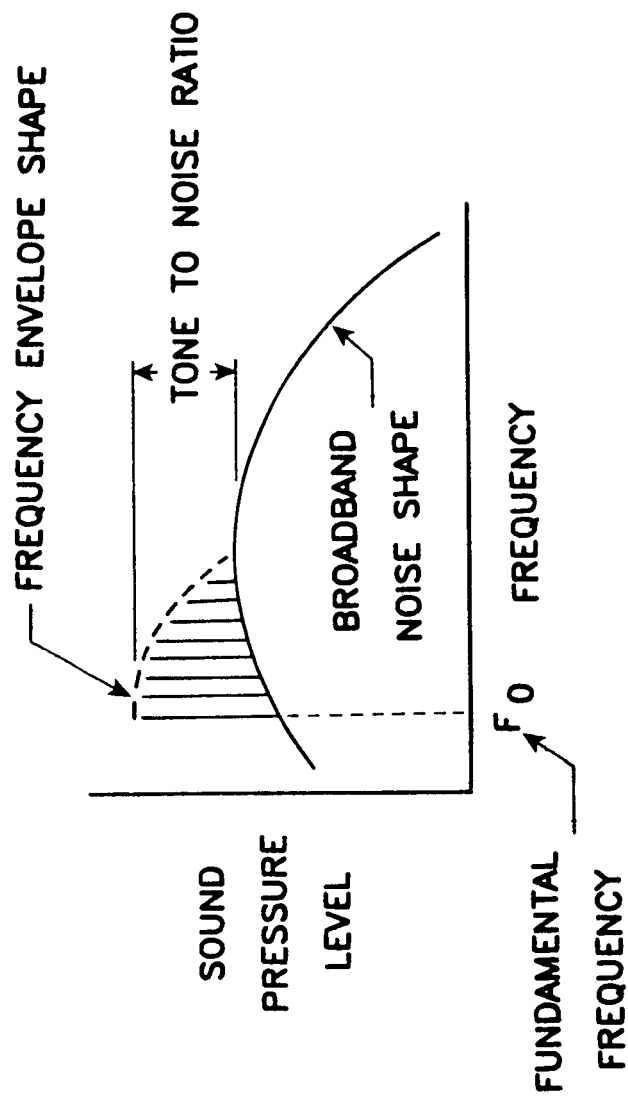


Figure 2. - Propeller aircraft noise characteristics.

ADVANCED TURBOPROP NOISE CHARACTERISTICS

The primary concern in quantifying advanced turboprop noise annoyance is the unique spectral characteristics of the noise. In general, propeller noise consists of a number of harmonically related pure tone components which are superimposed on broadband noise (fig. 2). The fundamental frequency of these tones, which can dominate the total noise produced by the aircraft, occurs at the propeller blade passage frequency and ranges from 50 Hz to about 150 Hz for conventional propeller aircraft. For advanced turboprop aircraft, the fundamental frequency is predicted to range from 150 Hz to as high as 300 Hz. The counter-rotating-propeller configuration also introduces a second set of harmonically related pure tone components, affects the frequency envelope shape (i.e., the sound pressure levels of the harmonics relative to the fundamental) and dramatically changes the directivity patterns of various tones. The annoyance caused by noise sources with strong tonal components has historically been more difficult to quantify than annoyance caused by broadband noise. The uncertainty in accounting for tonal content is increased in this case because less basic psychoacoustic research has been conducted in the lower frequency ranges of tones from conventional and advanced turboprop propellers than in the higher frequency range of tones from jet aircraft.

SYNTHESIS SYSTEM ORGANIZATION

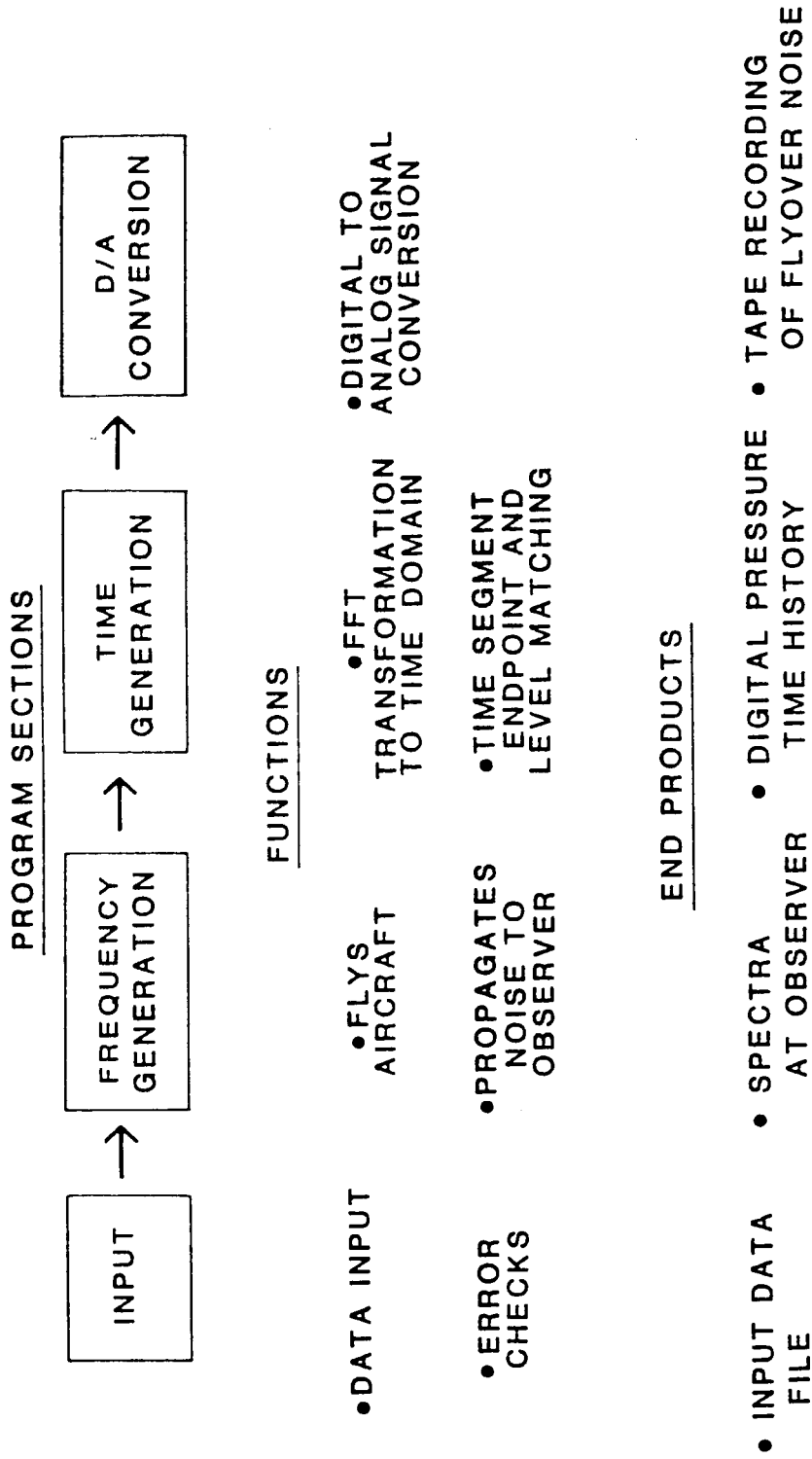
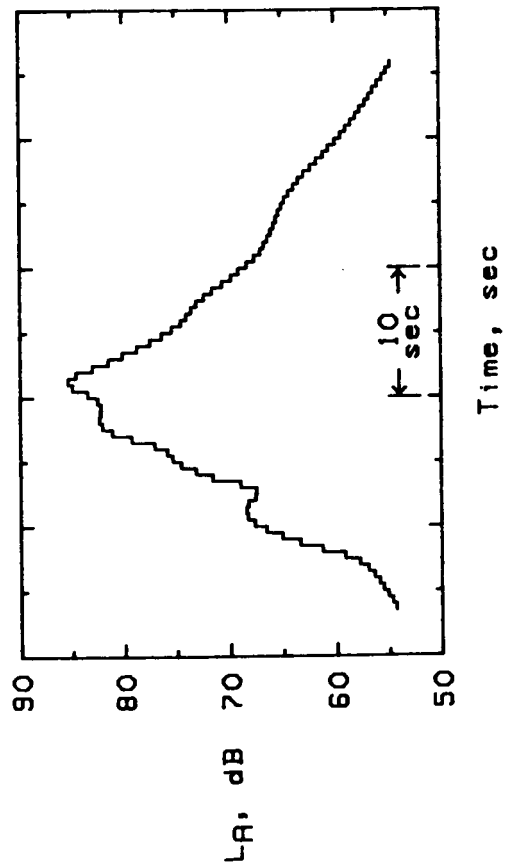
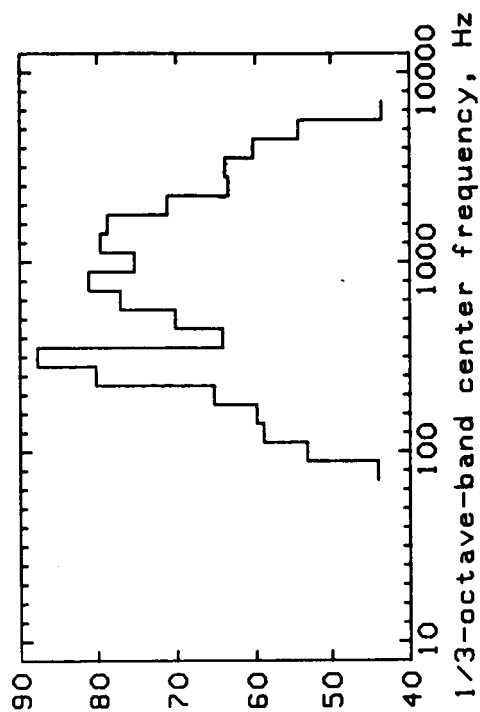
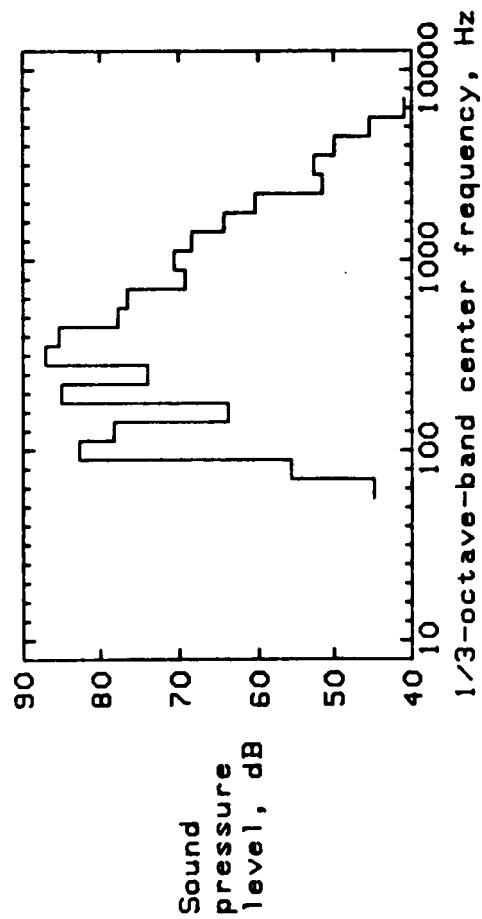


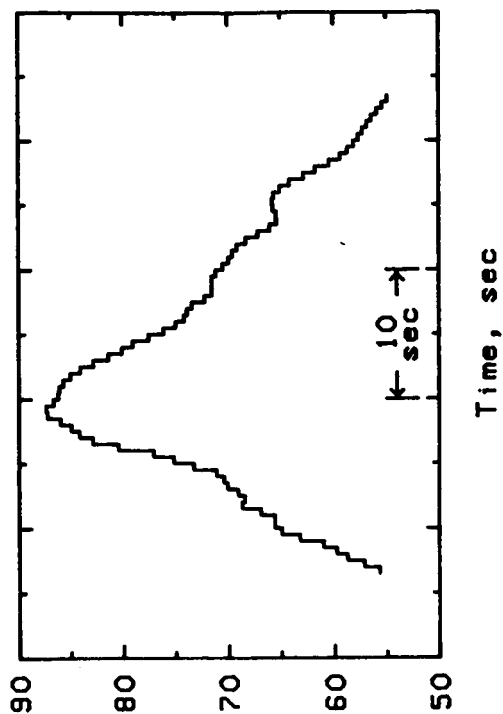
Figure 3. - Aircraft Noise Synthesis System

AIRCRAFT NOISE SYNTHESIS SYSTEM

A recently developed Aircraft Noise Synthesis System (fig. 3) was used to generate the advanced turboprop noise stimuli used in this experiment. The computer-based system generates realistic, time-varying, audio simulations of aircraft flyover noise at a specified observer location on the ground. The synthesis takes into account the time-varying aircraft position relative to the observer; specified reference spectra consisting of broadband, narrowband and pure tone components; directivity patterns; Doppler shift; atmospheric effects; and ground effects. These parameters can be specified and controlled in such a way as to generate stimuli in which certain noise characteristics such as fundamental frequency or duration are independently varied while the remaining characteristics such as broadband content are held constant.



(a) Fundamental frequency = 112.5 Hz



(b) Fundamental frequency = 292.5 Hz

Figure 4. - L_A time histories and one-third-octave band spectra at peak L_A of the highest level presentations of the advanced turboprop flyover noises with 30 dB tone-to-broadband noise ratios and fundamental frequencies of 112.5 and 292.5 Hz.

ADVANCED TURBOPROP NOISE STIMULI

The synthesis system was used to generate 27 simulations of advanced turboprop aircraft flyover noise in which the tonal content was systematically varied to represent the factorial combinations of nine fundamental frequencies (112.5, 135, 157.5, 180, 202.5, 225, 247.5, 270, and 292.5 Hz) and three tone-to-broadband noise ratios (0, 15, and 30 dB). (Tone-to-broadband noise ratio was defined to be the difference between the level of the fundamental tone and the level of the highest one-third-octave band of broadband noise). Typical time histories and one-third-octave band spectra are shown in figure 4.

The simulations were limited to one takeoff flight profile, one observer location, one broadband noise spectrum, one broadband noise directivity pattern, and one helical tip Mach number. Each of these parameters was the same for each simulation. The takeoff flight profile used resulted in an altitude at closest approach to the observer of 380 m, about the altitude expected at the FAR 36 takeoff noise measurement location (ref. 1). The observer was located on the centerline of the ground track. Since predictions of advanced turboprop broadband noise were not available, the broadband spectral content was based on measurements of an existing, large, turboprop aircraft. Aircraft speed was 70 m/sec. An aft-mounted, pusher, counter-rotating-propeller configuration with an equal number of blades on each rotor was assumed for all the simulations.

The tonal components, frequency envelope shape (i.e., the sound pressure level of the harmonics relative to the fundamental), and tone directivity patterns for each of the 27 advanced turboprop noise simulations were chosen based on a review of the available literature and preliminary wind tunnel data. This information was then used as input to the synthesis system. The fundamental frequencies were based on the numbers of blades, 5, 6, 7, 8, 9, 10, 11, 12, and 13, combined with an assumed rotation speed of 1350 rpm. Each of the 27 simulations was presented to the test subjects at D-weighted sound pressure levels of 70, 80, and 90 dB. The factorial combinations of nine fundamental frequencies, three tone-to-broadband noise ratios, and three levels resulted in 81 advanced turboprop aircraft flyover noise stimuli.

- 27 ADVANCED TURBOPROP TAKEOFFS
 - 9 FUNDAMENTAL FREQUENCIES — 112.5 to 292.5 Hz
 - 3 TONE TO BROADBAND NOISE RATIOS — 0, 15, 30 dB
 - GENERATED USING AIRCRAFT NOISE SYNTHESIZER
- 5 CONVENTIONAL TURBOPROP TAKEOFFS
 - P-3, YS-11, DASH-7, NORD 262, SHORTS 330
- 5 CONVENTIONAL JET TAKEOFFS
 - A-300, 707, 727, DC-9, DC-10
- 3 LEVELS
 - $L_D = 70, 80, 90$ dB

Figure 5. - Test stimuli.

CONVENTIONAL TURBOPROP AND JET NOISE STIMULI

A summary of the test stimuli is presented in figure 5. Takeoff recordings of five conventional turboprop aircraft (P-3, YS-11, Dash-7, Nord 262, Shorts 330) and five conventional jet aircraft (A-300, B-707, B-727, DC-9, DC-10) were included in the experiment. Each takeoff was presented at D-weighted sound pressure levels of 70, 80, and 90 dB for a total of 15 conventional turboprop noise stimuli and 15 conventional jet noise stimuli. The recordings of the jet aircraft were made on the extended runway centerline approximately 5000 m from the brake release point. The conventional turboprop aircraft all had maximum takeoff weights greater than 5700 kg. The turboprop aircraft recordings were made at several different airports and the distances from brake release varied. At each location, the turboprop aircraft recordings were made on or near the extended runway centerline. Because of the higher flight profiles and lower source noise levels of the turboprop aircraft, the recording sites for the turboprop aircraft were located closer to the brake release point than those for the jet aircraft.



Figure 6. - Subjects in anechoic test facility.

EXPERIMENTAL METHOD AND DESIGN

A small anechoic room in the Langley Aircraft Noise Reduction Laboratory was used as the test facility in the experiment (fig. 6). Sixty-four test subjects judged the annoyance of each noise stimulus using a numerical category scale. The scale was a unipolar, 11 point scale from 0 to 10. The end points of the scale were labeled "EXTREMELY ANNOYING" and "NOT ANNOYING AT ALL." The term "ANNOYING" was defined in the subject instructions as "UNWANTED, OBJECTIONABLE, DISTURBING, OR UNPLEASANT."

The means (across subjects) of the judgments were calculated for each stimulus. In order to obtain a subjective scale with meaningful units of measure, these mean annoyance scores were converted to "subjective noise levels," L_s , having decibel-like properties through the following process. Included in the experiment for the purpose of converting the mean annoyance scores to L_s values were five additional presentations of the B-727 takeoff recording ranging in values of L_D from 65 to 95 dB in 10 dB increments and at 99 dB. A second order polynomial regression analysis was performed using data obtained for the eight B-727 stimuli. The dependent variable was the calculated PNL and the independent variable was the mean annoyance score for each of the eight stimuli. The regression equation thusly determined was subsequently used to predict the level of the B-727 takeoff noise which would produce the same mean annoyance score as each of the other noise stimuli in the experiment. These levels were then considered as the "subjective noise level" for each stimulus.

Each stimulus was analyzed to provide one-third-octave band sound pressure levels from 20 Hz to 20 kHz for use in computing a selected group of noise metrics. These included the simple weighting procedures L_A , L_D , and L_E and the more complex calculation procedures LL , LL_z , PL , and PNL . Six different variations of each of the noise metrics were calculated. The first was the peak or maximum level occurring during the flyover noise. Two other variations were calculated by applying two different tone corrections. Three more variations were attained by applying duration corrections to the non-tone corrected level and the two tone corrected levels. The duration correction and the first tone correction, T_1 , are identical to those used in the effective perceived noise level procedure (EPNL) defined in the Federal Aviation Administration FAR 36 regulation (ref. 1). The second tone correction, T_2 , is identical to the first except that no corrections are applied for tones identified in bands with center frequencies less than 500 Hz.

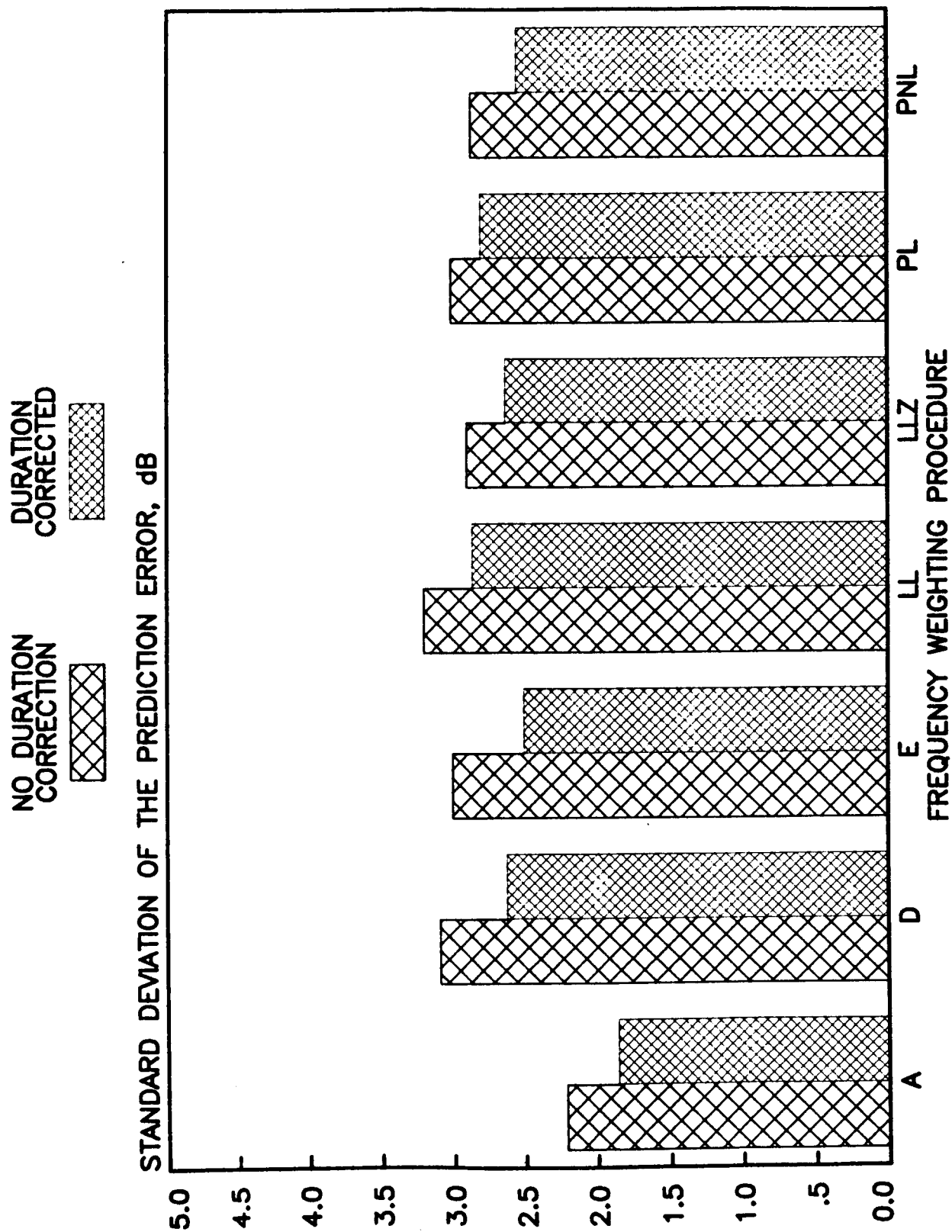


Figure 7. - Comparison of frequency weighting procedures for all aircraft.

COMPARISON OF FREQUENCY WEIGHTING PROCEDURES

In order to investigate the prediction ability of the noise measurement procedures and corrections, the differences between the subjective noise level and the calculated noise level for each of the six variations of each noise metric were determined for each stimulus. These differences were considered to be the "prediction error" for each stimulus and noise metric variation. The standard deviation of the prediction errors for each noise metric variation is a measurement of how accurately the noise metric predicts annoyance; the smaller the standard deviation, the greater the prediction accuracy. The results for all three types of aircraft combined are given in figure 7. The figure illustrates the standard deviations of prediction error, averaged across the different tone correction variations, for the seven noise metrics both with and without duration corrections. Comparisons of the results in figure 7 indicate that annoyance prediction was improved by the addition of duration corrections. LA had the smallest standard deviation of prediction error for both the duration corrected and uncorrected cases. It should be noted that, because of interrelationship between the data cases, statistical tests for significance of differences in the standard deviations of prediction error are not straightforward. Approximate statistical tests indicate that differences in standard deviations as small as 0.13 dB could be significant.

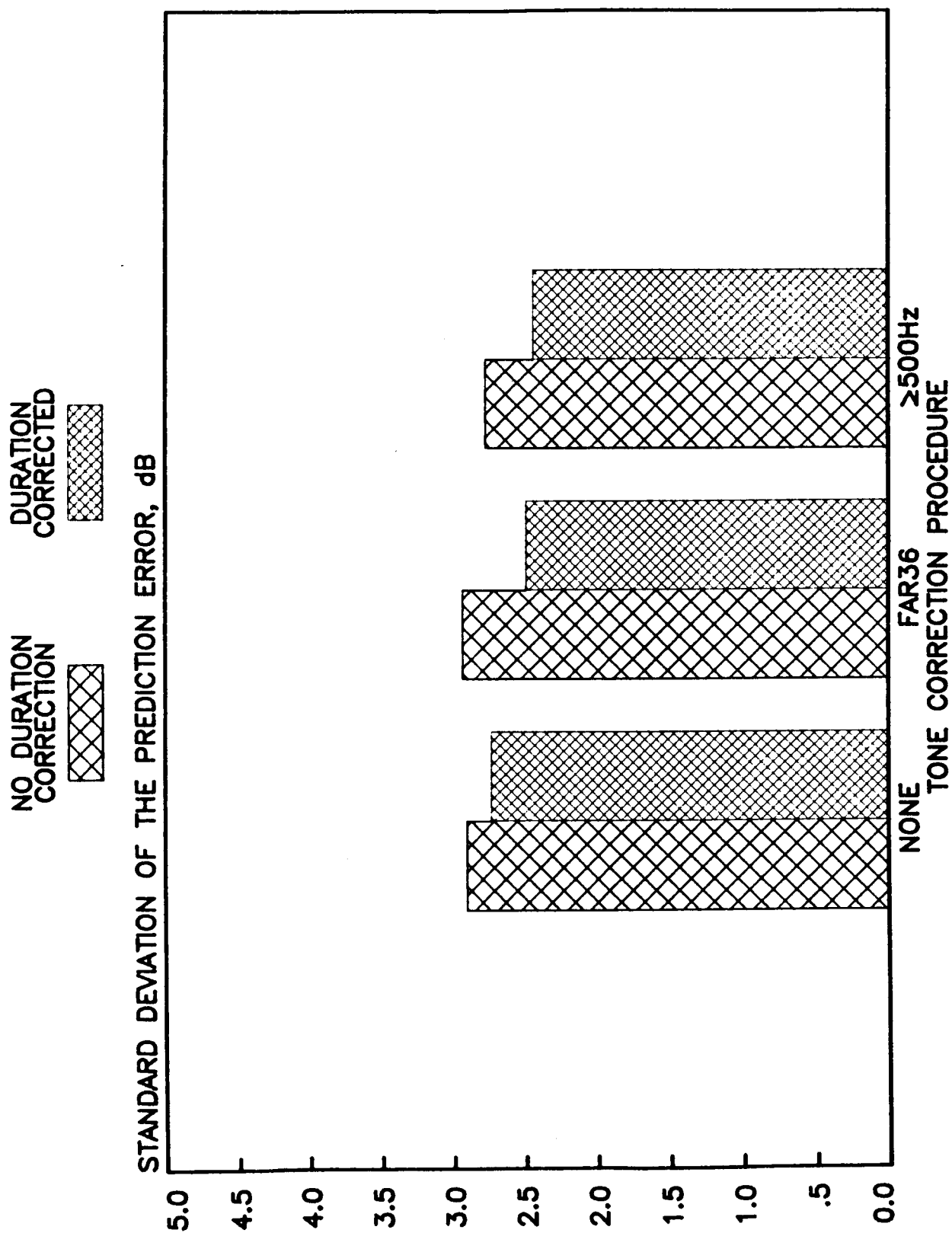


Figure 8. - Comparison of tone correction procedures when applied to PNL for all aircraft.

COMPARISON OF TONE CORRECTION PROCEDURES

Figure 8 compares the standard deviations of prediction error for the three variations of tone corrections when all three types of aircraft are combined. The figure plots the standard deviation of prediction error for each of the six variations of the PNL noise metric. For both the duration corrected and uncorrected cases, the modified tone correction, T_2 , which does not apply corrections for tones below 500 Hz, improved prediction ability more than the standard tone correction, T_1 . This result was consistent for almost all of the noise metrics considered and agrees with results from previous studies of propeller noise (ref. 3, 4).

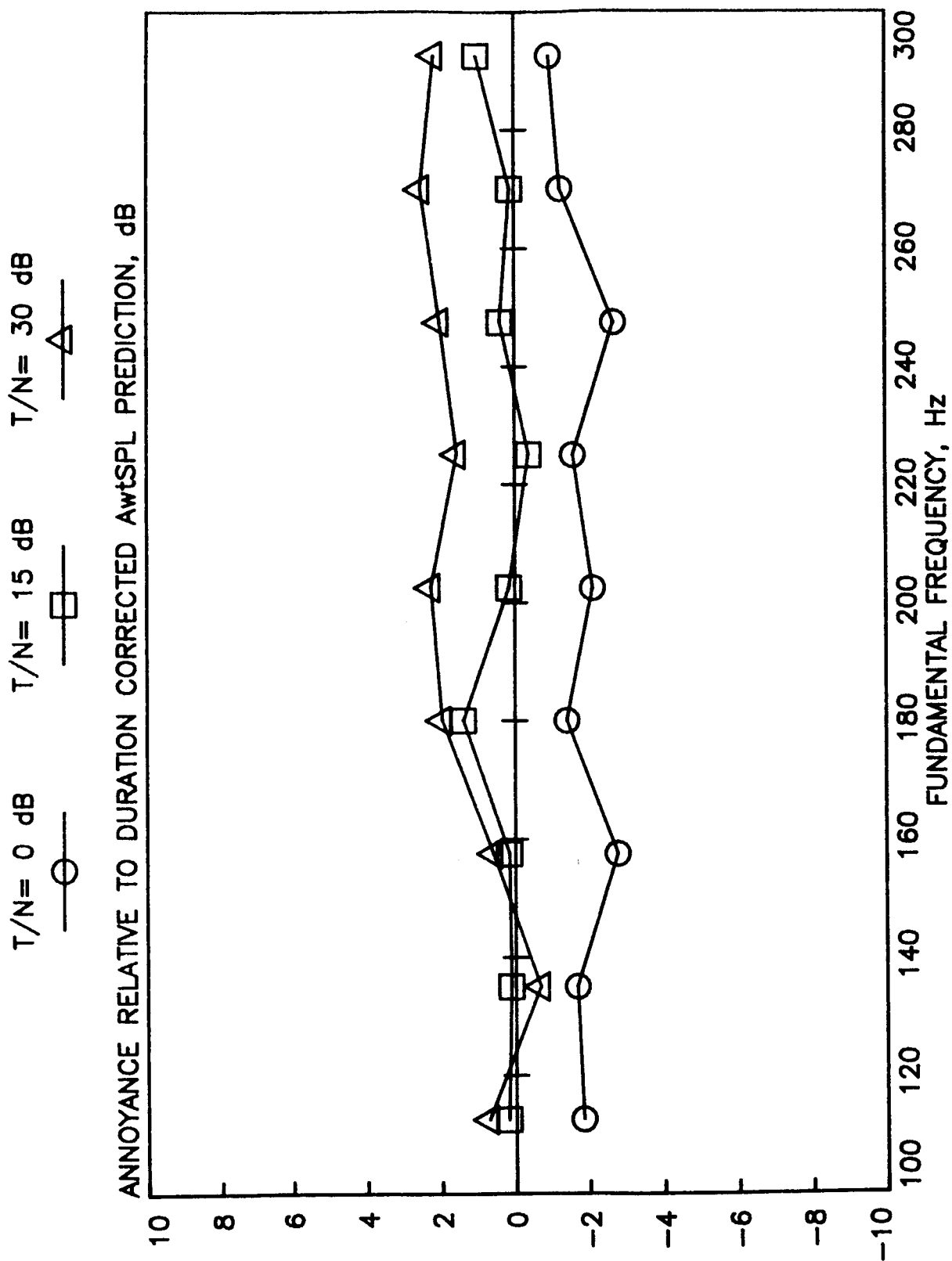


Figure 9. - Interaction of fundamental frequency and tone-to-broadband noise ratio for ATP stimuli in terms of duration corrected L_A .

INTERACTION OF FUNDAMENTAL FREQUENCY AND TONE-TO-BROADBAND NOISE RATIO -- DURATION CORRECTED LA

Figure 9 illustrates the effects of fundamental frequency and tone-to-broadband noise ratio on annoyance to the advanced turboprop flyover noises. The figure shows that the interaction of fundamental frequency and tone-to-broadband noise ratio did have an effect on annoyance. In the figure, annoyance relative to duration corrected LA is plotted versus fundamental frequency for each of the three tone-to-broadband noise ratios. "Annoyance relative to a metric" is the prediction error (subjective noise level minus the calculated level of the metric) normalized by subtracting the average prediction error for the metric. Thus a positive number represents annoyance greater than that predicted by the metric and results for different metrics can be directly compared. Annoyance increased as tone-to-broadband noise ratio increased except at the lower frequencies. For fundamental frequencies from 112.5 to 180 Hz there was no difference in annoyance between the 15 and 30 dB tone-to-broadband noise ratios. A similar study (ref. 4) of single-rotating-propeller configurations of advanced turboprop aircraft also found an interaction, but indicated the opposite effect of tone-to-broadband noise ratio. In that study, annoyance tended to decrease at higher tone-to-broadband noise ratios.

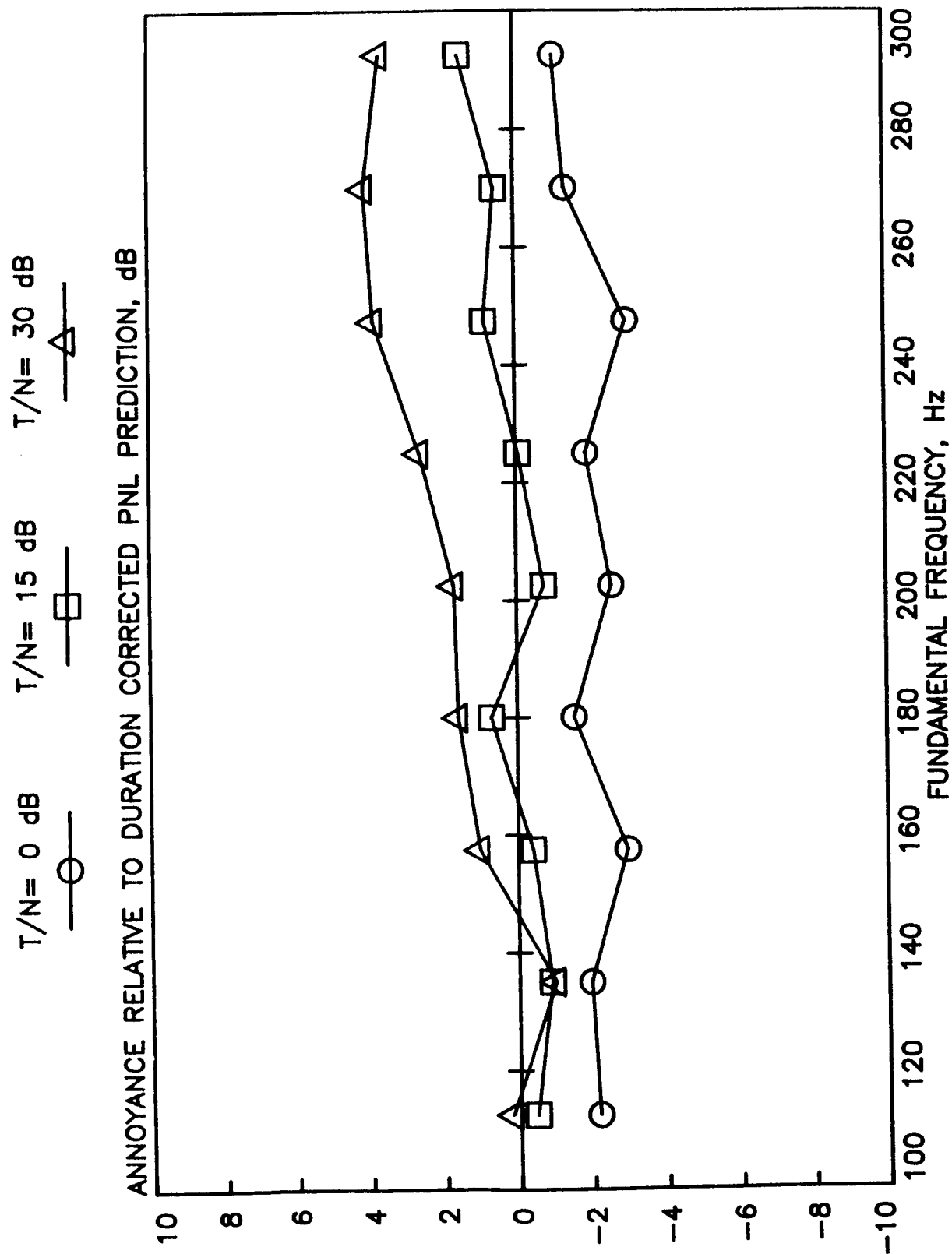


Figure 10. - Interaction of fundamental frequency and tone-to-broadband noise ratio for ATP stimuli in terms of duration corrected PNL.

INTERACTION OF FUNDAMENTAL FREQUENCY AND TONE-TO-BROADBAND NOISE RATIO -- OTHER METRICS

Figure 10 illustrates the interaction of fundamental frequency and tone-to-broadband noise ratio for duration corrected PNL. As in figure 9 for duration corrected L_A , an interaction is indicated. However, for duration corrected PNL the difference between the 30 dB tone-to-noise ratio and the lower ratios was slightly more in the higher frequencies. In general, the magnitude of the interaction varied considerably between the different combinations of noise measurement procedures and corrections.

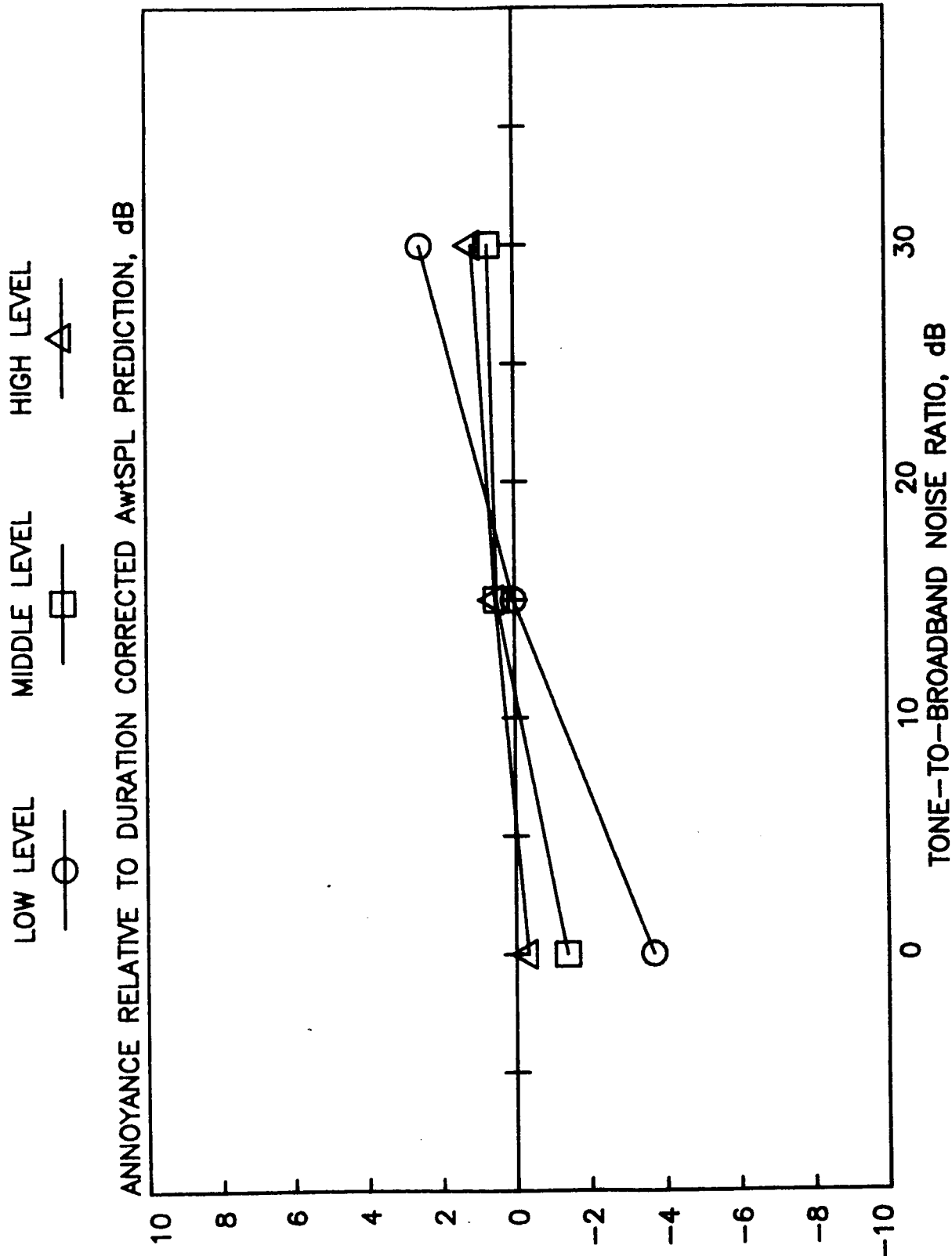


Figure 11. - Interaction of tone-to-broadband noise ratio and level for ATP stimuli in terms of duration corrected L_A .

INTERACTION OF TONE-TO-BROADBAND NOISE RATIO AND LEVEL

-- DURATION CORRECTED L_A

Figure 11 illustrates the effects of tone-to-broadband noise ratio and level on annoyance to the advanced turboprop noises. The figure shows that the interaction of tone-to-broadband noise ratio and level did have an effect on annoyance. In the figure, annoyance relative to duration corrected L_A is plotted versus tone-to-broadband noise ratio for each of the three levels at which the stimuli were presented to the test subjects. "Annoyance relative to a metric" is defined the same as in previous figures. Annoyance increased with tone-to-broadband noise ratio at a much greater rate for the low level stimuli than it did for the middle and high level stimuli.

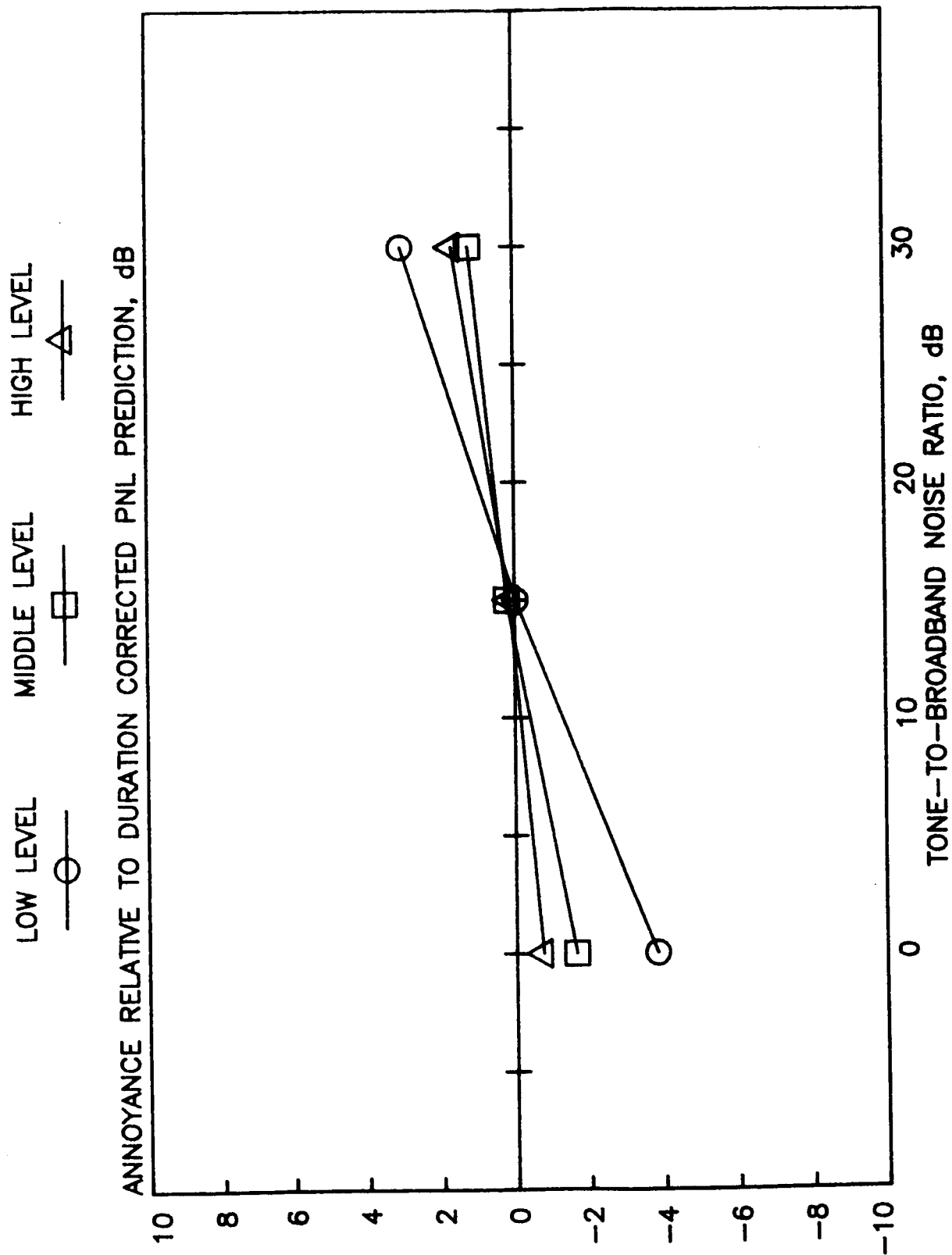


Figure 12. - Interaction of tone-to-broadband noise ratio and level for ATP stimuli in terms of duration corrected PNL.

INTERACTION OF TONE-TO-BROADBAND NOISE RATIO AND LEVEL

-- OTHER METRICS

Figure 12 illustrates the interaction of tone-to-broadband noise ratio and level for duration corrected PNL. As in figure 11 for duration corrected L_A , an interaction is indicated. In general, the interaction was similar for all combinations of noise measurement procedures and corrections, except that in some cases, the annoyance of the middle and high level stimuli did not increase with tone-to-broadband noise ratio.

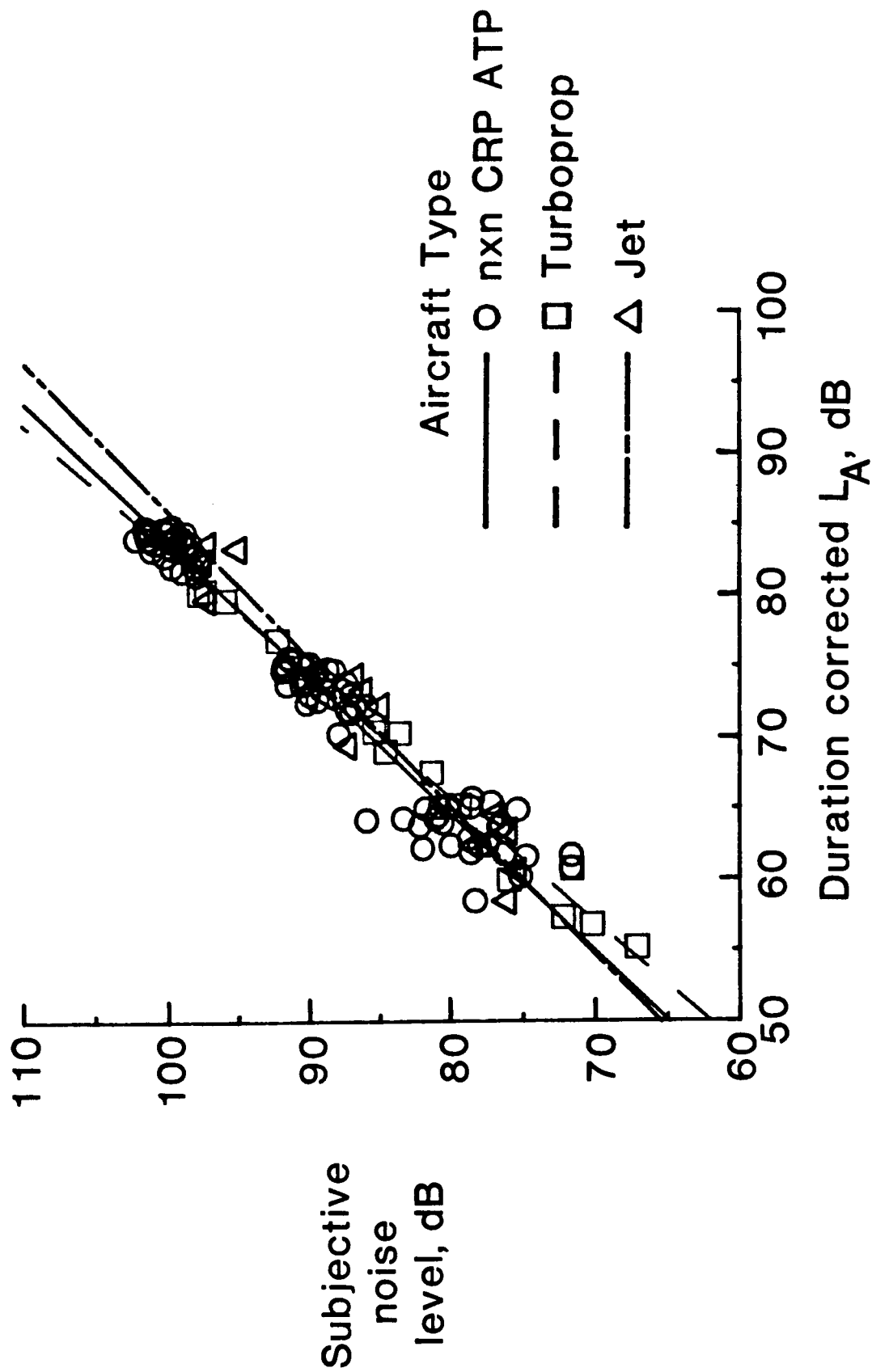


Figure 13. - Comparison of annoyance responses using duration corrected L_A .

COMPARISONS OF ANNOYANCE RESPONSES BETWEEN AIRCRAFT TYPES -- DURATION CORRECTED L_A

Figure 13 compares the annoyance responses to advanced turboprop, conventional turboprop and conventional jet aircraft flyover noises. The figure plots subjective noise level versus duration corrected L_A for each of the three categories of aircraft. Simple linear regression lines for each of the aircraft types are also shown. Indicator (dummy) variable analyses for the duration corrected L_A metric found no significant differences in slope or intercept between the appropriate regressions for the advanced turboprop noises, the conventional turboprop noises, and the conventional jet noises. For duration corrected L_A , annoyance to all three categories of aircraft can be represented by one simple linear regression equation.

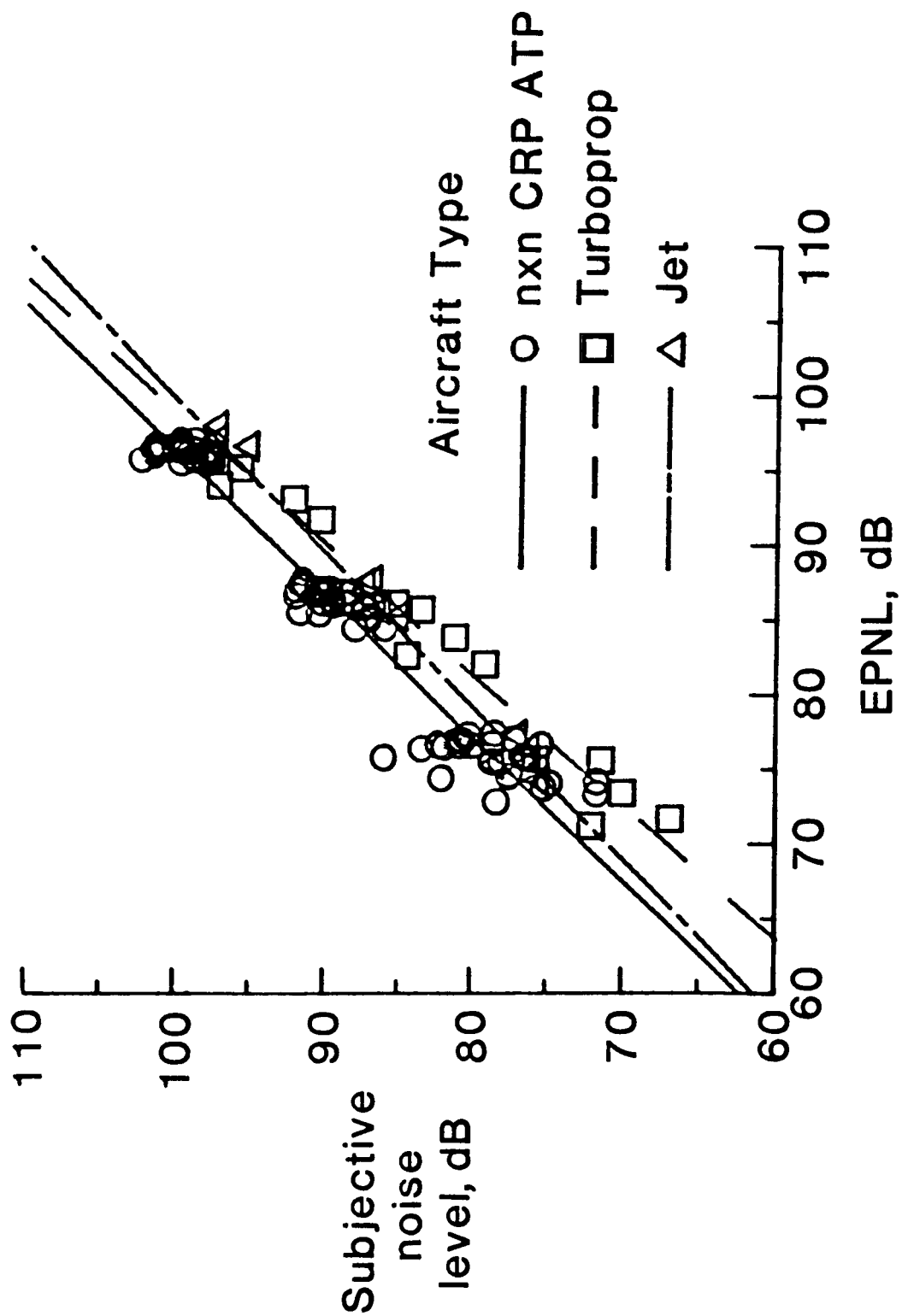


Figure 14. - Comparison of annoyance responses using EPNL.

COMPARISON OF ANNOYANCE RESPONSES BETWEEN AIRCRAFT

TYPES -- OTHER METRICS

Figure 14 compares the annoyance responses to advanced turboprop, conventional turboprop, and conventional jet aircraft flyover noises using EPNL. For EPNL, indicator variable analyses show a significant difference in intercept, but not slope, between the appropriate regressions for the combined set of advanced turboprop and conventional jet noises and the conventional turboprop noises. The conventional turboprop noises were slightly less annoying than the combined set of advanced turboprop and conventional jet noises. Almost all the metrics considered yielded the same result. No differences between the advanced turboprop noises and the conventional jet noises were found for any metric.

SUMMARY

A laboratory experiment was conducted to quantify the annoyance of people to the flyover noise of advanced turboprop aircraft with counter-rotating propellers having an equal number of blades on each rotor. Sixty-four test subjects judged the annoyance of 81 advanced turboprop, 15 conventional turboprop, and 15 conventional jet aircraft flyover noise stimuli in an anechoic listening facility. The following preliminary results were noted:

- Duration corrections improved annoyance prediction
- Limiting tone corrections to tones at or above 500 Hz improved annoyance prediction
- A-weighted sound pressure level had the smallest standard deviation of prediction error
- The interaction of fundamental frequency and tone-to-broadband noise ratio did have a significant effect on annoyance response
- The interaction of tone-to-broadband noise ratio and level did have a significant effect on annoyance response
- No differences in annoyance response between the advanced turboprops and the conventional jets were found. For most metrics, the conventional turboprops were found to be slightly less annoying than the other aircraft.

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